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Review

Mining in the Arctic environment – A review from ecological, socioeconomic and legal perspectives

Anne Tolvanen[a,b,*], Pasi Eilu[c], Artti Juutinen[a,d], Katja Kangas[a], Mari Kivinen[c], Mira Markovaara-Koivisto[c], Arto Naskali[e], Veera Salokannel[f], Seija Tuulentie[e], Jukka Similä[f]

[a] Natural Resources Institute Finland, P.O. Box 413, FI-90014 University of Oulu, Finland
[b] Department of Genetics and Ecology, FI-90014 University of Oulu, Finland
[c] Geological Survey of Finland, P.O. Box 96, FI-02151 Espoo, Finland
[d] Department of Economics, FI-90014 University of Oulu, Finland
[e] Natural Resources Institute Finland, Eteläranta 55, FI 96300 Rovaniemi Finland
[f] Faculty of Law, University of Lapland, P.O. Box 122, FI-96101 Rovaniemi Finland

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ABSTRACT

The development of mining and other resource-based industries are among key drivers of economic development in the Arctic. The fragile environment and the presence of nature-based livelihoods and indigenous communities pose challenges for mining development. Mining operations should be optimized so that the profitability is maintained in changing market conditions and to meet increasing societal and environmental demands. In this study we present the current understanding on the interplay between mining and the surrounding socio-ecological systems in the Arctic region. The existing academic literature on the Arctic region was reviewed, covering 127 peer-reviewed publications since 2000. We investigated the mining activities from four perspectives examining: 1) environmental, 2) economic, 3) social and 4) legal dimensions, covering three life-cycle stages: 1) pre-mining, 2) mining, and 3) post-mining. The publications on the environmental and economic aspects focused principally on the impacts of mining, whereas social and legal publications discussed the interaction between people and their rights and ways of controlling their environment. Besides the need for more balanced research between different life-cycle stages we uncovered five research gaps concerning the knowledge base needed to increase the sustainability of Arctic mining: 1) impacts and adaptation to climate change, 2) monitoring the sustainability of mining using standardized indicators, 3) holistic economic assessment of mining, 4) social sustainability and conflict management, and 5) mechanisms that mitigate or compensate for the adverse effects of mining on biodiversity.

1. Introduction

The attractiveness of mineral resources in the Arctic has increased and the region is seen as a vast storehouse of potential resources (Lindholt, 2006; Emmerson and Lahn, 2012; Boyd et al., 2016). The attractiveness reflects not just the geology, but also the availability and coverage of geodata, availability of professional workforce, level of infrastructure, and the predictability of administrative and legal decision-making (Noras, 2016). As a result, the development of mining and other resource-based industries are among the key drivers of economic development in the Arctic (Tuusjärvi et al., 2014; Tiainen et al., 2014; Bay-Larsen et al., 2018).

The fragile Arctic environment and the presence of nature-based livelihoods and indigenous communities pose challenges for mining development. Increasing human activities are intermingled with the climate change that is advancing more rapidly in the Arctic region than elsewhere. Hence the consequences of mining on ecosystems and societies may be more dramatic than elsewhere. The current debate over the legacy and sustainability of mining, in general, arises from detrimental environmental and social impacts and their cumulative effects on socio-ecological systems (e.g., Davis, 2009). There may be economic benefits for local communities, but at the same time there may also be degrading impacts on the environment (Heikkinen et al., 2002, 2009) which are reflected to local cultures and livelihoods (Holley and

* Corresponding author. Natural Resources Institute Finland, P.O. Box 413, FI-90014 University of Oulu, Finland.
E-mail addresses: anne.tolvanen@luke.fi (A. Tolvanen), pasi.eilu@gtk.fi (P. Eilu), artti.juutinen@luke.fi (A. Juutinen), katja.kangas@luke.fi (K. Kangas), mari.kivinen@gtk.fi (M. Kivinen), mira.markovaara-koivisto@gtk.fi (M. Markovaara-Koivisto), arto.naskali@luke.fi (A. Naskali), veera.salokannel@ulapland.fi (V. Salokannel), seija.tuulentie@luke.fi (S. Tuulentie), jukka.simila@ulapland.fi (J. Similä).

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Table 1
Selected statistics on the Arctic. The area included is as shown in Fig. 1. Russia is divided into European and Asian parts.

Country	Land area in the Arctic, km^2	Population density, per km^2	Mineral production USD/ km^2	Mineral production USD per capita	Mineral strategy (year)	References[c]
Alaska	1,717,856	0.43	1974	4911	20,08[a]	Anon. (2015b), U.S. Census Bureau (2012, 2015)
Arctic Canada	4,365,111	0.03	776	26,205	2004–2015[b]	Anon. (2004, 2009, 2013c, 2015a), Statistics Canada (2016)
Arctic Finland	168,262	3.95	11,201	3717	2010	Anon. (2010), National Land Survey (2016), Pokki (2016), Statistics Finland (2016)
Arctic Norway	112,963	4.26	2026	5986	2013	Anon. (2013a), Statistics Norway (2016)
Arctic Sweden	151,929	3.35	20,022	2832	2013	Anon. (2013b), Statistiska centralbyrån (2012)
Greenland	2,166,086	0.03	0	0	2014	Anon. (2014), Statistics Greenland (2016)
Russia, Asia	7,490,700	0.44	1642	1679	2008[a]	Federal State Statistics Service (2004)
Iceland	102,775	3.24	0	0	1998[a]	Statistics Iceland (2016)
Russia, Europe	1,329,600	2.67	795	3103	2008[a]	Federal State Statistics Service (2004)
Svalbard	61,022	0.04	1829	42,235	2013	Anon. (2013a), Statistics Norway (2016)
Total Arctic	17,666,304	0.55				
Global data	148,940,000	48.42				World Population Statistics (2014), World by Map (2015)

[a] Mining Act (entirely new or a significant amendment to an older law).
[b] Nunavut 2004, 2009, North-Western Territories: 2013, Yukon 2015.
[c] For mineral strategies in Finland, Greenland, Iceland, Norway, and Sweden, see also Hojem (2015).

Mitcham, 2016; Johnsen, 2016). Mining companies are challenged to optimise their operations so that profitability is maintained in changing market conditions and increasing societal demands (Bridge, 2004; Törmä et al., 2015; Johnsen, 2016).

Since 2004, most Arctic countries and regional administrations have produced or updated their mineral strategies (Table 1). This may not only be a result of the improved political understanding and the economic significance of mining, but also a consequence of increased awareness of the environmental and the social effects of mining. That is, there is a better awareness of the increasing importance of gaining and maintaining a social licence to operate (SLO) (Prno and Slocombe, 2012; Koivurova et al., 2015a).

Assessing the impacts and sustainability of mining activities that are experienced by the surrounding socio-ecological systems requires a holistic approach. Existing frameworks include the triple bottom line (TBL) and the Five Capital (5 CAPS) approaches developed to assess sustainable development (SD). The TBL approach considers dimensions of the environment, economy and society. The Global Reporting Initiative (GRI) Mining and Metals Sector Supplement (2011) employs this approach to provide guidance for reporting on the sustainability of mining companies. The 5 CAPS method delineates natural, financial and manufactured capital combined with society-based assets of human skills and social capital (Uhlmann et al., 2014). The 5 CAPS method was originally developed to obtain theoretically sound and policy relevant comparisons between countries' welfare and sustainability (Kulig et al., 2010). However, there is less attention paid to legal aspects in these approaches.

In this paper, we present the current understanding on the interplay between mining and the surrounding socio-ecological systems in the Arctic region (Fig. 1). Inspired by TBL and the 5 CAPS theoretical approaches, our analytical framework covers four distinctive although interlinked dimensions including: 1) environmental, 2) economic, 3) social and 4) legal dimensions. To consider the whole life cycle of mining we divided mining operations into three stages: pre-mining, mining, and post-mining. We assumed that research concerning each

Fig. 1. The 'Circumpolar Arctic' as shown on the Arctic Council website (www.arctic-council.org/index.php/en/learn-more/maps). This is the geographic area we consider in this paper. Original image by Winfried Dallmann.

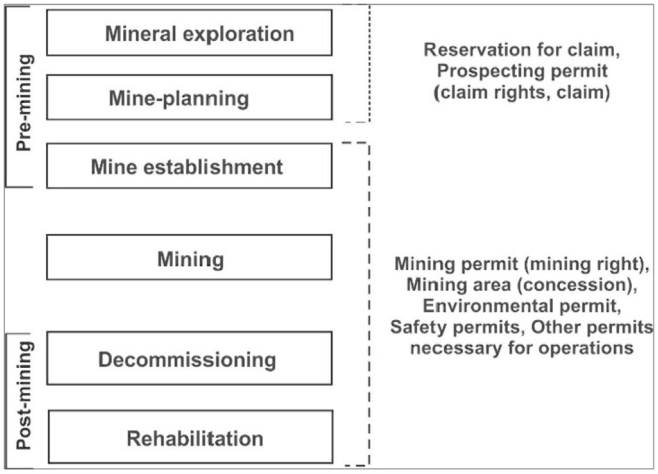

Fig. 2. Life-cycle stages of a mine with an overview of the permits needed. Mining permits may include, e.g., ore exploitation, environmental and safety permits, and vary extensively between jurisdictions. Modified after Heikkinen et al. (2005) and Kauppila et al. (2011).

individual dimension at any of the three stages of mining operation would be vital to create a balanced knowledge base for sustainable mining in the Arctic. We reviewed the existing academic literature on the Arctic region, covering 127 peer-reviewed publications since 2000. We asked the following questions: i) what has the focus been in the research in terms of the dimensions and life cycle stages? ii) does the research provide a balanced knowledge base for a sustainability assessment of Arctic mining, and finally iii) are there research gaps and lessons to learn considering the sustainability of mining in the Arctic region?

2. The life cycle of mines

The life cycle of mines in the Arctic is similar to elsewhere, but the fragile Arctic socio-ecological systems and harsh climate have to be taken into account at all stages of mining operation. The life cycle includes three main stages: 1) pre-mining, 2) mining, and 3) post-mining (Heikkinen et al., 2005; Durucan et al., 2006; Kauppila et al., 2011; Drielsma et al., 2016) (Fig. 2). Each stage may include several operational and permitting steps, and in many cases, different life cycle stages co-exist. During the mining stage, suspension (temporal closure) sometimes occurs, when the production is halted for the interim as a result of low commodity prices, for example. This is especially common in mines operating close to their break-even point (Crowson, 2009).

The time needed for each operational stage varies greatly depending on technical, economic, environmental and legal factors in force (Durucan et al., 2006; Kauppila et al., 2011; Drielsma et al., 2016). Individual mine project may typically last from 20 to 50 years, but can extend to hundreds of years for very large mines (Eilu et al., 2012). Post-closure monitoring can last for decades (e.g., Heikkinen et al., 2009; Drielsma et al., 2016). To be able to proceed beyond the exploration stage, the quality of a mineral resource has to be high enough to ensure profitable mining. In an overwhelming majority of the cases, the work is halted already in the initial exploration stage (Kauppila et al., 2011; Bennet et al., 2014).

3. Material and methods

Key thematic aspects of each dimension were identified as keywords that we expected to be found in the literature (Table 2). The environmental dimension covered the literature on soils, waters, and the living biota such as plants and animals, waste issues, and reclamation activities. We expected that most environmental publications would be on the ecological and environmental impacts of mining. The economic dimension covered both the direct and indirect impacts at regional and local levels. We also expected that the literature would cover cost-benefit analyses of mining operations in particular at the pre-mining stage to evaluate the social profitability of establishing a new mine. The social dimension covered issues related to social capital such as participation, networks and trust (Putnam, 1993). Community-corporate relations, such as voluntarily negotiated agreements and cooperative arrangements, power relations and the role of indigenous people were also expected to be present. The legal dimension covered research publications focussing on impact assessments, land-use planning and permission, land claims and self-governance agreements, company self-regulation as well other legal aspects of governance.

Table 2
Specific keywords used in the literature search.

Environmental	Economic	Social	Legal
avian	economic	climate change	indigenous people
biodiversity	impacts	community	rights
bird	regional	fly in fly out	land-use plans
climate change	impacts	indigenous people	law
environment	socio-economic	local	regulation
fauna	impacts	regional	self-regulation
mammal	willingness to	development	social corporate
plant	pay	social	responsibility
pollution		social license to	permitting
soil		operate	environmental
vegetation		society	impact assessment
waste			social impacts
water			assessment
wildlife			benefit agreements

We searched for peer-reviewed environmental, economic and social studies, and legal studies using mainly, but not exclusively, Google Scholar. Reference lists of the found publications were also searched. The main keywords were 'mine', 'mining', 'mine closure', or 'mineral extraction', which were used in combination with the specific keywords in each dimension listed in Table 2. We selected Arctic studies using the keyword 'Arctic' or the Arctic countries and regions as shown in Fig. 1. Concerning the studies in Finland, Sweden, Norway and the European part of Russia, our review is restricted to the Barents region, as it represents the characteristics of Arctic regions in terms of ecological, economic, and social factors. In Iceland, there has been very little mining, none of which considers metals (Franzson et al., 2016), and the forecasts for future mining suggest little activity. Hence, Iceland was excluded from this review.

The focus was on metals (uranium included), coal and industrial minerals (gypsum, phosphate). Oil, gas, and construction materials (e.g. gravel, sand) were excluded, as their extraction permitting policy and environmental impacts are different from the aforementioned. Deep-sea mining was also excluded, although the impacts of land-based mines on marine ecosystems were included. The review contains publications since the year 2000, because the recent mining boom started in the 2000s. Only publications containing original research data were included.

The literature search resulted in 127 publications on metal, coal, and gemstone mining since 2000. We arranged the publications into 12 categories which were related to the four main dimensions and the three main stages in the mining life cycle. Of the publications, 49 focussed on the environmental dimension, 10 on the economic dimension, 38 on the social dimension, and 30 on the legal dimension. Mineral exploration, mine-planning and mine-establishment were classified as pre-mining stages, and all non-operating mines (historical, closed, and suspended mines) were classified into the post-mining category. Almost a third (39) of the publications focussed on Arctic Canada. The rest focussed on Greenland (18), Arctic Sweden (16), Arctic Finland (14), Alaska (10), European Russia (8), Arctic Norway

Table 3
Publications on the environmental dimension according to main topic and life-cycle stage (no. of publications in brackets).

Main topic	Mining stage	Authors
Marine and aquatic ecosystems (17)	All stages (1)	Søndergaard (2013) (also terrestrial lichens)
	Mining (5)	Holopainen et al., (2003), Quakenbush and Citta (2009), Salmelin et al., (2017), St-Gelais et al., (2017), Tkatcheva et al., (2004)
	Post-mining (11)	Dang et al., (2017), Elberling et al., (2002), Elberling et al., (2003), Foster et al., (2008), Gray et al., (2000), Josefson et al., (2008), Larsen et al., (2001), Sonne et al., (2014), Sternal et al., (2017), Søndergaard et al., (2010), Søndergaard et al., (2011)
Terrestrial ecosystems, soils and vegetation (14)	Mining (8)	Brumbaugh et al., (2011), Chen et al., (2017), Heikkinen et al., (2002), Heikkinen et al., (2009), Naeth and Wilkinson (2008), Neitlich et al., (2017), Pugh et al., (2002), Walker et al., (2003)
	Mining, post-mining (1)	Virtanen et al. (2002)
	Post-mining	Askaer et al., (2008), Bhattacharya et al., (2006), Dowdall et al., (2004), Elberling et al., (2007), Närhi et al., (2012)
Reclamation (8)	Mining (7)	Artimo et al., (2004), Boldt-Burisch and Naeth (2017), Drozdowski et al., (2012), Reid and Naeth (2005a), Reid and Naeth (2005b), Stoltz and Greger, 2002a, Stoltz and Greger, 2002b
	Post-mining (1)	Coulson et al. (2015)
Animal tissue and health (5)	Mining (3)	Brumbaugh et al., (2010), Koch et al., (2005), Saunders et al., (2011)
	Mining, post-mining (1)	Berglund et al. (2010)
	Post-mining (1)	Amuno et al. (2016)
Wildlife behaviour and distribution (5)	Mining (2)	Smith et al., (2005), Walton et al., (2001)
	Pre-mining, mining (3)	Boulanger et al., (2012), Johnson et al., (2005), Weir et al., (2007)

(6), Svalbard (4), and from two or more Arctic countries simultaneously (12). There were no publications focussing on the Russian Arctic on the Asian side In the next chapter we describe the main focus in each dimension.

4. Results

4.1. The environmental dimension (49 publications)

The environmental dimension covered the ecological and environmental impacts of mining, principally at the local level, although some publications assessed vegetation impacts (Virtanen et al., 2002) or animal behaviour (Johnson et al., 2005) also at the regional level. The time perspective of the publications varied from short-term impact studies to an assessment after a century of mining operations. The emphasis was on the mining and post-mining stages, and none of the publications concentrated exclusively on the pre-mining stage (Table 3, Fig. 3). Most publications were from Canada and Greenland, and metal commodity mines were the main type of mine. Due to the large variety of publications it was reasonable to classify them into main themes in addition to the three life-cycle stages. The main themes used were the impacts of mining on marine and aquatic ecosystems (17 publications), impacts on terrestrial ecosystems, soils and vegetation (14), reclamation (8), terrestrial animal tissue and health (5), and wildlife behaviour and distribution (5) (Table 3).

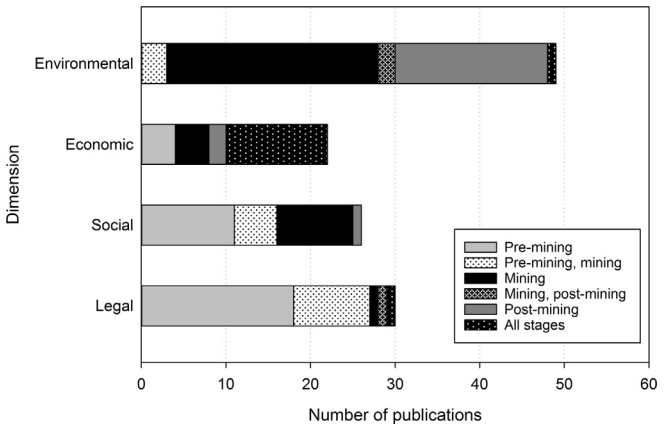

Fig. 3. Number of peer-reviewed publications in different dimensions and life-cycle stages.

The impacts of mining on marine or aquatic ecosystems were assessed principally during the post-mining stage. The deposition of submarine tailings is a major source of impact for the marine coastal environment, which was observed to cause long-term accumulation of metals in sediments and biota (Dang et al., 2017; Elberling et al., 2002; Larsen et al., 2001; Søndergaard et al., 2010, 2011; Sonne et al., 2014; Sternal et al., 2017). Despite elevated concentrations of Hg in fish (Gray et al., 2000) and As and Cu in bearded seals (Quakenbush and Citta, 2009), no evidence was found of levels causing health risks for people. The distribution and colonization of the biota was changed (Elberling et al., 2003; Josefson et al., 2008; St-Gelais et al., 2017), and an extreme example showed altered microbial communities at sites from early 1900s where mining of volcanogenic massive sulfide deposits had taken place (Foster et al., 2008).

Most of the publications concentrating on terrestrial ecosystems, soils and vegetation investigated the effects of acid mine drainage during the mining or post-mining stages. Acid mine drainage caused by the oxidation of sulphidic mining waste is a common and long-term problem in coal and metal (e.g. Ni, Cu, Zn, Fe) mines (Heikkinen et al., 2002, 2009). The runoff waters contain elevated concentrations of heavy metals, which can reach phytotoxic levels in native plants (Pugh et al., 2002; Elberling et al., 2007; Askaer et al., 2008) and reduce plant diversity (Närhi et al., 2012). Heavy metals can also disperse as dust and concentrate in snow, soil and plant tissues (Walker et al., 2003; Brumbaugh et al., 2011; Chen et al., 2017; Neitlich et al., 2017). Nevertheless, some plants were observed to be tolerant to metals (Bhattacharya et al., 2006; Naeth and Wilkinson, 2008; Närhi et al., 2012), which was a promising result for the potential use of these plants for the phytostabilization of metalliferous soils in the Arctic region.

The eight publications concentrating on the reclamation of mining areas described work carried out principally in the mining stage. The re-establishment of vegetation was seen as crucial as it counteracts erosion, the redeposition of tailings materials by wind (Reid and Naeth, 2005a), and the spread of acidic elements or metals into waters (Stoltz and Greger, 2002b; Artimo et al., 2004). The addition of fertilizers and structure-improving amendments were observed to improve physical and chemical soil properties and promote plant growth (Reid and Naeth, 2005a, b, Drozdowski et al., 2012), and the application of topsoil had a long-term effect on the soil fungal community (Boldt-Burisch and Naeth, 2017). The establishment of metal-tolerant plants such as

Salix and graminoids were observed to stabilise metals, but the concentrations might still be toxic to grazing animals (Stoltz and Greger, 2002a, b).

The accumulation of harmful elements in vegetation can be magnified within ecosystems via food webs. The animal tissue and health publications concentrated on small birds or small mammals during the mining and post-mining stages of metal mining. Despite heavy metal accumulation in the tissues of small mammals and birds, no remarkable health effects were found in most of the studied animals (Brumbaugh et al., 2010; Amuno et al., 2016). Arsenic (As) generally increases in soils, food, water, and dust near gold mines and was observed to increase also in the tissues of small mammals (Saunders et al., 2011). Birds were thought to be adapted to increased arsenic levels due to their ability to form relatively nontoxic forms of As in their tissues (Koch et al., 2005). We found no studies that addressed the element accumulation in large terrestrial mammals such as moose or reindeer, which are important in the human diet in the arctic region, or on large predators.

The five wildlife behaviour and distribution publications described work carried out during the mining stages, three also discussed the pre-mining stage (Johnson et al., 2005; Weir et al., 2007; Boulanger et al., 2012). The publications consistently demonstrated that wildlife avoid mining areas. Especially mines but also exploration activities had a negative effect on species occurrence (Johnson et al., 2005). Avoidance was observed in most seasons (Weir et al., 2007; Boulanger et al., 2012), but especially during the breeding season (Walton et al., 2001; Weir et al., 2007). On the other hand, mines provided habitats for at least one bird species benefiting from human impacts (Smith et al., 2005).

4.2. The economic dimension (10 publications)

The economic dimension focused on the direct and indirect impacts of mining at local and regional levels. Indirect impacts included multiplier effects on other economic sectors as well as effects on economic structure. There was no clear emphasis on any certain mining stage. Four publications concentrated on the pre-mining stage, four on the mining stage and two on the post-mining stage in terms of potential closure of productive mines (Fig. 3). The economic publications were further classified into three main themes: 1) economic impact assessments (8 publications), 2) enhancement of business development (1), and 3) environmental valuation (1) (Table 4).

A common focus in the economic impact assessments were the direct, indirect and induced employment impacts of mining projects. Mining has remarkable local and regional economic impacts especially in the developed arctic regions such as Sweden and Finland (Ejdemo and Söderholm, 2011; Ejdemo, 2013; Törmä et al., 2015). The outcome was relevant for all three mining stages and the impacts spread into other sectors, in particular the private service sector, supporting regional economic development in rural areas (Ejdemo and Söderholm, 2011; Tano et al., 2016; Moritz et al., 2017). There were, however, inter-country differences in the impacts (Ejdemo, 2013; Tano et al., 2016; Moritz et al., 2017). In addition, mining booms were complex and occurred due to multiple causes (Kröger, 2016). In the frontier regions such as Yukon in Canada, the regional economic impacts (of mine closures) were not dramatic, because of the 'decoupled' nature of the staple economy with rather weak local economic linkages. The major impact of mine closures was found in induced effects, related to economic and demographic shifts in the household sector followed by changes in consumption (Petrov, 2010).

The study examining how to increase the business potential in the mining sector focused on the transition from an economic cluster to a collaborative community in Greenland (Kadenic, 2015). Collaboration represents a new approach to business and industrial development in remote regions of the Arctic to overcome the limitations of smallness and the sometimes inadequate competencies of the business community. Management of the transition to a collaboration community requires a shared service provider that performs supporting activities.

The environmental valuation study provided monetary information on mining externalities (Kosenius and Horne, 2016). The study examined the welfare effects of a mining plan in the Oulanka-Ruka area in Finland. The Oulanka National Park in the study area has about 180,000 visitors annually. The bedrock is rich in several metals and there have been plans to open new mines in the area. The monetary value of the non-market benefits revealed the importance of mining externalities, such as the visibility of the mine, increased traffic and noise, affected species, and recreational possibilities, for decision makers in a commensurate manner. The aggregated annual welfare loss for national park visitors resulting from the implementation of the mining plan ranged from 30 million Euros to 100 million Euros, depending on which externalities were considered. The monetary estimates did not reflect the real monetary transfers in the local and regional economy as the impact assessment studies do. However, the results indicated that the implementation of the mining plan would likely have a significant negative impact on nature-based tourism in the area.

4.3. Social dimension (38 publications)

Social issues are often discussed in relation to all mining stages, and the community time scales differ from the mining time scales as the communities usually stay while mines come and go. Due to the differences in the time scales, it was often difficult to distinguish each study's relationship with the different mining stages. However, eight of the publications could be clearly seen as focussing on the pre-mining stage, three on the mining stage and one on the post-mining stage (Fig. 3). Four publications referred both to mines that once existed but also examined forthcoming mining activities. The main research themes were local communities' attitudes and development questions in regard to mining (14 publications), the social license to operate (SLO) (8), indigenous communities' relationship to mining (7), impact and benefit agreements (IBA) (3), land use (2), governance (2) and climate change (2) (Table 5).

Studies on small mining communities showed that in resource-based communities mining dominates the community and diversification of the economy is difficult (Knobblock and Pettersson, 2010; Suutarinen, 2013; 2015a, 2015b). Based on the studied mine closure scenarios, it was clear that mining had failed to produce lasting social and economic development when its holistic impacts on wellbeing were considered (Rixen and Blangy, 2016). To stimulate long-term regional employment growth it is therefore important to make strategic decisions that also promote other livelihoods than mining (Knobblock and Pettersson, 2010). There is also a need to listen to the local community's voices and

Table 4
The number of publications on the economic dimension according to the main topic and life-cycle stage (no. of publications in brackets).

Main topic	Mining stage	Authors
Economic impacts (8)	Pre-mining (2)	Ejdemo and Söderholm (2011), Ejdemo (2013)
	Mining (4)	Haley et al., (2011), Kröger (2016), Moritz et al., (2017), Tano et al., (2016)
	Post-mining (2)	Petrov (2010), Törmä et al., (2015)
Business development (1)	Pre-mining	Kadenic, 2015
Environmental valuation (1)	Pre-mining	Kosenius and Horne (2016)

Table 5
The number of publications on the social dimension according to the main topic and life-cycle stage (no. of publications in brackets).

Main topic	Mining stage	Authors
Local communities (14)	All stages (5)	Kadenic (2015), Knobblock and Pettersson (2010), Suopajärvi et al., (2016), Suutarinen (2015b), Thorén Hedin and Ranängen 2017
	Mining (6)	Nilsson (2010), Storey (2010), Storey (2016), Suutarinen (2013), Suutarinen (2015a), Tarras-Wahlberg et al., (2017)
	Pre-mining (1)	Bjørst (2016)
	Pre-mining, mining (1)	Hansen et al., 2016
	Post-mining	Rixen and Blangy (2016)
SLO (8)	Mining (1)	Prno (2013)
	Pre-mining (3)	Holley and Mitcham (2016), Lyytimäki and Peltonen (2016), Tarras-Wahlberg (2014)
	Pre-mining, mining (4)	Prno and Slocombe (2012), Heikkinen et al., (2016), Koivurova et al., (2015a), Lesser et al., (2017)
Indigenous issues (7)	All stages (1)	Davison and Hawe (2012)
	Pre-mining (2)	Dahlberg-Grundberg and Örestig (2017), Espiritu (2015), Lawrence and Larsen, 2017
	pre-mining, post-mining (3)	Cater and Keeling (2013), Dana and Anderson (2014), Procter (2016)
IBA (3)	All stages (1)	Caine and Krogman (2010)
	Pre-mining (2)	Hitch and Fidler (2007), Missens et al., (2007)
Land use (2)	Pre-mining	Hébert and Brock (2017), Johnsen (2016)
Governance (2)	All stages	Haikola and Anshelm (2016), Tiainen (2016)
Climate change (2)	Mining	Ford et al., (2010), Pearce et al., (2011)

to create trust between them and mining operations (Bjørst, 2016; Hansen et al., 2016; Suopajärvi et al., 2016). Participation should be made possible throughout the entire life cycle of the mine (Suopajärvi et al., 2016). Various ways of organizing the community involvement and concerns with mining processes were identified, and understanding the community and using its input for decision making was emphasized (Tarras-Wahlberg et al., 2017, Thorén Hedin and Ranängen, 2017).

Specific cases raised in relation to community involvement included single-industry communities where mining dominated the local community (Suutarinen, 2013; 2015a; Nilsson, 2010). One example is Kiruna in northern Sweden, where local residents were observed to be so dependent on the mining company that they did not dare to criticize the need for the relocation of the entire town of Kiruna, only the performance of the process (Nilsson, 2010). Due to the problems associated with creating the whole community around mining, fly in and fly out operations have been increasing lately especially in Canada and Alaska. Still, also in these cases the relationships with the existing communities need to be arranged (Storey, 2010).

Four of the seven publications concentrating explicitly on indigenous issues discussed the situation in various mining cases in the Canadian Arctic (Cater and Keeling, 2013; Dana and Anderson, 2014; Davison and Hawe, 2012; Procter, 2016). Interestingly, they all referred to the historical development of mining in the region, and noted that, despite conflictual issues, the communities have developed in tandem with mining. However, it was also acknowledged that mining did not last long and the environmental impacts are large, and there were bad experiences with earlier mines which affect the present attitudes (Dana and Anderson, 2014). There was also a conflictual situation in planning mines in Sámi region in northern Scandinavia (Dahlberg-Grundberg and Örestig, 2017; Lawrence and Larsen, 2017). As well in the Canadian as in the northern European context, the question was about the greater international recognition of the indigenous peoples' rights over their traditional territories and natural resources therein. The emerging norm is that the consent of indigenous communities is required prior to extractive activities taking place on indigenous lands and where their rights are affected (Lawrence and Larsen, 2017).

The social license to operate (SLO) and impact and benefit agreements (IBAs) were referred to in some of the above mentioned publications but there were altogether 11 concentrating specifically on these issues. Similarly to the community publications, these studies emphasized the importance of transparency in the process and the involvement and participation of local communities. Prno and Slocombe (2012, see also Prno, 2013) pointed out that each SLO is unique. The concept of SLO was regarded as coming close to the wider concepts of sustainability and corporate social responsibility (Koivurova et al., 2015a). IBA, which have until now not been made between mining companies and indigenous communities except in Russia, could be seen as a tool to secure SLO (Prno and Slocombe, 2012). The difficulties of IBAs were seen in spelling out how the agreements would be monitored and how violations of the agreements would be addressed (Caine and Krogman, 2010) and also in the idea that the IBAs may not reflect the collective voice of the community (Hitch and Fidler, 2007).

Climate change was discussed in relation to Canadian mining companies. It was concluded that mines are affected by climate events which are indicative of climate change but that most industry stakeholders view climate change as a minor concern, and no actions have been taken so far (Ford et al., 2010; Pearce et al., 2011).

4.4. The legal dimension (30 publications)

The emphasis of the 26 journal publications and 4 book chapters was clearly on the pre-mining stage. 18 publications focused solely on the pre-mining stage and 10 publications covered this together with other stages (Fig. 3). A half of the publications (15) concerned indigenous people and these were further divided into three categories: rights of indigenous communities in relation to mining projects (9), agreements between mining companies and indigenous people (3), and land claims and self-governance agreements (3). Other than focussing on indigenous people, the publications were divided into two groups focussing on: impact assessment and permitting (11), and other legal issues (4) (Table 6).

The nine publications focussing on the rights of indigenous communities typically claimed that the current legal regime does not effectively protect traditional livelihoods and support the involvement of indigenous people in decision-making. For example, in Norway, the legal framework regulating Sami interests remained unclear and did not require a social impact assessment (Nygaard, 2016). Although the legislation is progressive in Greenland as it requires obligatory environmental and social impact assessments and even an IBA, this is not a guarantee of success if the implementation fails (Hansen and Mortensen, 2013). Mining projects have not met the principle requirements of free, prior and informed consent in Greenland (Hubbard, 2014). A Canadian case study criticized the ability of a court to take into account the views of indigenous people in a mining case (Ariss and Cutfeet, 2011), and in Russia the lack of financial support and public control hampered the realization of legislation dedicated to improving the living standards of indigenous people (Garipov, 2014). Even though the Sami people in Finland enjoy strong protection against the adverse impacts of mining especially in their homeland region (Koivurova and Petrétei, 2014), a comparative study between Norway, Sweden, Finland and Russia concluded that none of the legislations is ideal and one can hardly decide which one gives the most protection for Sami people

Table 6
The number of publications on the legal dimension according to the main topic and life-cycle stage.

Main topic	Mining stage	Authors
Rights of indigenous communities (9)	Pre-mining (6)	Ariss and Cutfeet (2011), Garipov (2014), Hansen and Mortensen (2013), Hubbard (2014), Koivurova et al. 2015a,b, Nygaard (2016)
	Pre-mining, mining (3)	Koivurova and Petrétei (2014), Mortensen (2012), Mortensen (2015)
Agreements (3)	Pre-mining (2)	Couch (2002), Laforce et al., (2009)
	All stages (1)	Campbell and Prémont (2017)
Land claims and self-governance (3)	Pre-mining (2)	Bowman (2011), Göcke (2013)
	Pre-mining, mining (1)	Kentch (2011)
Impact assessment and permitting (11)	Pre-mining (7)	Ackrén (2016), Noble and Bronson (2005), Koivurova et al., (2014), Parker et al., (2008), Pettersson et al., (2015), Suopajärvi (2013), Söderholm et al., (2015)
	Pre-mining, mining (4)	Doelle (2012), Fauchald (2014), Kokko et al., (2015), Solbär and Keskitalo, 2017
Other legal issues (4)	Pre-mining (1)	Bjørgo and Bay-Larsen (2017)
	Pre-mining, mining (1)	Nysten-Haarala et al. (2015)
	Mining (1)	Olszynski (2010)
	Mining, post-mining (1)	Nevskaya et al. (2016)

(Koivurova et al. 2015a,b).

Agreements between a mining company and an indigenous community often complete legal regulation. A case study from Canada presented a two-step process consisting of an environmental impact assessment that was followed by parallel permitting and negotiated agreements. The process was useful as it resolved an array of interdependent policy, environmental, social impact, legal/administrative and economic issues (Couch, 2002). Despite the example, asymmetrical power relations may make it generally difficult to integrate the true positions of indigenous people into the process of making agreements (Campbell and Prémont, 2017; Laforce et al., 2009).

Land claims and self-governance agreements (3 publications) provide another layer for the governance structures and are important for the decision making of indigenous people. However, land claim agreements have resulted in centralization of environmental governance and reduced accountability because a small group of people can exert discretionary control over vast areas. Participatory rights ensured in public law do not always apply to agreements (Bowman, 2011; Kentch, 2011; Göcke, 2013).

Eleven publications focussed on impact assessments and permitting in general, i.e., without focussing on indigenous people. Many deficiencies in regulation were identified, such as the lack of an obligatory social impact assessment in Finland (Suopajärvi, 2013) and vague environmental standards to protect fish, game, wildlife, and habitats in Alaska (Parker et al., 2008). In Norway, there were several weaknesses in the environmental regime relevant for mining, such as the reliance on local authorities, unclear division of competence between authorities, and the devolution of power to public authorities without clear duties (Fauchald, 2014). Deficiencies in the implementation of legislation were also observed, such as the poor integration of health impacts into an environmental impact assessment in Canada (Noble and Bronson, 2005) and incomplete communication of expert knowledge to the wider audience in Norway (Bjørgo and Bay-Larsen, 2017). Despite improvements in regulation that have recently occurred in Finland, Sweden and North-West Russia, true institutional change is a long-term process and rarely involves radical transformation (Pettersson et al., 2015).

The remaining four publications concerned self-regulation (1), adaptive management (1) and mining waste (2). Effective self-regulation is important although it is not a guarantee for achieving SLO in Finland and Sweden. Global industrial standards may lack public trust, if monitoring is not arranged in a legitimate and independent way (Nysten-Haarala et al., 2015). Applying adaptive management approaches to the mining industry may provide benefits, although a failure to implement any step of this approach can unravel its potential (Olszynski, 2010). For example, conflicts between mining and environmental law, inconsistency of accounting systems, and undeveloped institutions were found to be the main reasons hindering the development of mining waste management in Russia (Nevskaya et al., 2016).

5. Discussion

The measurement of the sustainability of economic development or a particular economic activity is a challenging task which lacks a single, generally accepted approach. Our framework included four dimensions that aimed to capture the full complexity of the phenomena. Given this framework, the reviewed publications covered a wide spectrum of sustainability factors. Although we could enhance the knowledge base for sustainability assessment, establishing an overall picture of the sustainability of mining operations is not easy on the basis of highly specialized publications.

Environmental sustainability implies that the limited natural resources are used so that the continued development and life of future generations is ensured (IUCN, UNEP & WWF, 1991). In social sustainability the interdependence between human well-being, healthy environments and lively economies is emphasized (Moldan et al., 2012). In economics, sustainability is defined as the capacity to provide non-declining future welfare, which is dependent on the availability of capital (Pearce and Atkinson, 1993). Therefore, economic sustainability is typically operationalized by defining different forms of capital, such as man-made, financial, human, natural and social capital, evaluated in monetary terms (UNECE, 2009). Although the reviewed publications did not directly measure or evaluate sustainability, for example in terms how the mining changes different forms of capital stocks, they provided information on many indicators that have been used to measure sustainability (see, e.g., Kulig et al., 2010; Uhlmann et al., 2014).

5.1. The interplay between the four dimensions

Publications focussing on the environmental and economic dimension principally examined the local or regional impacts of mining, whereas social and legal publications discussed the complex interaction between people and their rights and ways to control their environment. Although the focus on the environmental dimension comprised almost a half of the publications, our review does not necessarily provide a comprehensive view on the amount of information available on the different dimensions. Many social, economic and legal issues are not

Arctic specific. Hence the research aiming to highlight mining related issues in any rural region is often relevant also to the Arctic. In fact, many environmental issues are not Arctic specific either, but the cold Arctic conditions pose greater challenges to the ecosystems compared to many ecosystems in warmer climate.

Changes in the natural environment caused by mining are often, albeit not always, reasons that economic and social impacts occur. These changes are reflected in public or private steering mechanisms which aim to avoid or at least mitigate the detrimental environmental, economic and social impacts. The reviewed environmental publications produced quantified information on principally negative and often long-term impacts of mining on the environment, biodiversity, animal health and behaviour. Although specific scientifically documented environmental data was not, and is rarely used *per se* in the other dimensions, environmental information is crucial to evaluate the acceptability of the impacts, to set limits on mining operations and to find solutions to mitigate the damage. For example, affected species and noise were considered as indicators of environmental deterioration in the economic dimension when examining the environmental valuation of mining externalities (Kosenius and Horne, 2016). The selection and classification of the status of mining externalities was based on literature on environmental impacts and on co-operation with experts.

The interplay between the environmental and social dimension was revealed indirectly in discussing the deterioration of the environment due to mining and the loss of lands used for traditional livelihoods such as herding. These issues were discussed especially in relation to SLO and indigenous peoples' rights (Lawrence and Larsen, 2017). The same topics are increasingly gaining attention in legal literature, which aims to provide a basis for making strategic decisions on mining. According to the reviewed social and legal dimension publications, there seems to be concern about the sufficiency of present mechanisms to safeguard the environment, other livelihoods, and indigenous peoples' rights under mining development. For example, environmental and other relevant legislation was criticized for being ineffective because environmental standards may be vague (Parker et al., 2008). An obligatory SLO process is still missing in many countries (Suopajärvi, 2013; Nygaard, 2016), and the current legal regime may not effectively support the involvement of indigenous people in decision-making (Nygaard, 2016). Nevertheless, in some areas decision-making structures include strong demands to take indigenous peoples' rights into account (Espiritu, 2015; Koivurova et al., 2015b). SLOs have also taken on a more institutionalized form, e.g. impact and benefit agreements (IBA) have been made with regard to indigenous populations (Prno, 2013).

Publications describing the economic dimension were thematically similar to those describing the social dimension especially when the employment effects of mining and the need for societal services were discussed. A difference in economic impacts between Arctic frontier regions or small resource-based communities and developed Arctic regions was revealed. In Arctic frontier regions, mining may fail to produce lasting economic and social developments (Rixen and Blangy, 2016). This is because mining has weak direct linkages to local economies, and therefore, its major impacts occur in the household sector through economic and demographic shifts that are followed by changes in consumption (Petrov, 2010). In developed Arctic regions, such as northern Sweden and Finland, the positive economic impacts of mining typically spread to other sectors and support regional economic development (Törmä et al., 2015; Tano et al., 2016). However, there may be conflicts with other nature-based livelihoods and industries, such as reindeer herding and tourism (Kosenius and Horne, 2016; Brown et al., 2017). Another challenge is the difficulty to find skilled workers and service providers (Ejdemo, 2013), and the provision of public and societal services, such as housing, day care, schools and healthcare for mining workers and their families because the scale of mining operations is enormous in relation to the surrounding communities. To increase public and societal services, large scale investments may be needed, which involves a risk, as mining activities are sensitive to economic fluctuations. During an economic boom, mines are likely to produce profits, employment and tax revenues for the communities. During a downturn, mines may be temporarily or permanently closed (Mason, 2001; Petrov, 2010; Törmä et al., 2015), which reduces the socio-economic benefits and creates uncertainty (Waye et al., 2009; Rolfe and Windle, 2015; Tiainen, 2016).

5.2. Life-cycle stages

There were clear differences between the publications focussing on different dimensions concerning their emphasis on the life-cycle stages. Based on the evaluation, we suggest some research topics to balance the knowledge base on the different mining stages.

Publications on the environmental dimension focused principally on the mining or post-mining stages and lacked studies concentrating exclusively on the pre-mining stage. The environmental effects during exploration are less evident than those during the mining stage, which may be one reason for the lack of papers on the pre-mining stage. Preparations for successful mine closure and reclamation should be in place already in the initial stages of mine planning and updated throughout the life of a mine (Kauppila et al., 2011). This calls for scientific studies and method development already at the pre-mining stage. Reclamation studies carried out beyond the Arctic region also focus principally on the mining and post-mining stages (e.g. Kim and Owens, 2010; Prach and Tolvanen, 2016; Puga et al., 2015; Ram and Masto, 2010). Besides, they may not provide sufficient information due to the harsh arctic conditions where species composition is different, recovery is slow and environmental impacts are generally long-lasting. Predictive modelling provides possibilities for exploiting limited empirical data for proactive planning (Kangas et al., 2016) and to mitigate or even avoid the most adverse environmental effects. In the reviewed publications, predictions and modelling were used only in three cases as a means to simulate and evaluate the effects of industrial development on animal distributions (Johnson et al., 2005; Boulanger et al., 2012) or to prepare for protection and reclamation of ground water (Artimo et al., 2004).

In contrast to the environmental dimension, most publications on the legal dimension concentrated on the pre-mining stage. This is not surprising considering this is the stage when the most important and influential regulatory decisions are made. For example, environmental impact assessments are carried out at the pre-mining stage and these include mitigation and reclamation plans, many of which come into force in the mining or post-mining stages. Most environmental impacts are caused during the mining stage and some of the impacts are unpredictable. Since mining operations continue for decades, regulatory decisions made at the pre-mining stage may have become outdated by the time of the mine closure. Hence, research on the legal dimension regarding environmental monitoring, regulatory responses to monitoring results, waste-management and non-compliance issues would provide valuable information which could improve the adaptiveness of legal instruments to changes occurring during mining operations (Olszynski, 2010). Research on legal mechanisms that ensure the reclamation of mining sites is also needed, since potential changes in the global and local markets, bankruptcies and changes in mine ownership increase the risk that the responsibility for the reclamation is left to the surrounding society or the government after a mine closure. While there are national-level publications on environmental liability in bankruptcy of a mining company (e.g. Linna, 2016), also international scientific publications from situations where local administrations may have only minor financial resources, require attention.

No clear bias towards a certain life-cycle stage was observed in the publications on the economic and social dimensions. Social issues were often discussed in relation to all mining stages, and hence the life cycle stage is not a significant classifier of the research. Relatively many publications examining the economic dimension focused on the pre-mining stage, but it was somewhat surprising that there was only one

environmental valuation study on the topic (Kosenius and Horne, 2016). The opening of a new mine will typically cause many ecological, economic and social effects in the surrounding environment, and therefore, a cost-benefit analysis that accounts for both market and nonmarket values could provide valuable information to authorities who decide on mining licenses (see, e.g., Carson et al., 1994). Environmental valuation methods could also be used to provide knowledge about public preferences for mine site reclamation (Burton et al., 2012).

Concerning both economic and social dimensions, one of the life-cycle stages receiving relatively little attention was the post-mining stage in terms of what happens in the community after a temporary or permanent mine closure. Mining is strongly driven by global economic cycles of supply and demand (e.g., Radetzki et al., 2008; Humphreys, 2010, Rosen, 2016). Besides strategic decisions to stimulate long-term regional employment growth (Knobblock and Pettersson, 2010), the development of benefit-sharing mechanisms might ensure that local people benefit from mining operations and to support the diversification of the economy at local and regional levels.

5.3. Knowledge gaps

Research gaps related to the mining stages were mentioned in the previous chapter, but thematic research gaps were also identified. Here we discuss five research topics that would increase the knowledge base to help promote sustainable mining in the Arctic: 1) impacts and adaptation to climate change, 2) monitoring the sustainability development of mining in the Arctic region through standardized indicators, 3) holistic economic valuation of mining, 4) social sustainability and conflict management, and 5) mechanisms that mitigate or compensate for the adverse effects of mining.

Climate change is a global scale topic, which, apart from two publications focussing on the social dimension (Ford et al., 2010; Pearce et al., 2011), was considered relatively little in the reviewed publications. Climate warming is more pronounced in the Arctic than in other regions in the world (IPCC, 2014). The changes in ecosystem processes are also greater and may have a more noticeable influence how environments respond to mining. For example, the release of acid mine drainage is normally limited by permafrost, but it may increase due to warming (Ford et al., 2010; Hollesen et al., 2011). This might lead to a relatively greater increase in the accumulation of heavy metals in the environment and biota. Along with the warming climate, the risk of alien species invasion may also increase, as the warming climate becomes better suited to species adapted to warmer climates (Coulson et al., 2015). On the other hand, warming temperatures may have relatively higher positive impacts on the recovery at some post-mining reclamation sites. Environmental changes may be reflected in local economies and societies, e.g. through changes in carrying out nature-based livelihoods (Lyytimäki and Peltonen, 2016; Nygaard, 2016), and may affect mining operations through changes in transportation routes, mining infrastructure, and carbon emission trading (Pearce et al., 2011). These changes can be reflected in the legal dimension through the need to adapt environmental decision-making to changing conditions (Olszynski, 2010; Benson, 2009).

Regardless of the dimension, most studies were local, regional and country specific (exception: Koivurova et al., 2015a). Despite that the information in these studies can often be generalized for other regions or countries, there are differences both in the impacts of mining but also in the way they are measured and regulated. Cross-national comparison across the Arctic region needs the development of data on direct measures of the impacts of mining based on similar methodologies and definitions (Haley et al., 2011). Standardized indicators that measure various dimensions of sustainability would provide a way to compare the development over large regions. The sustainability concept includes concerns for future generations and, hence, sustainability indicators could be used to determine trends in relation to accepted or target levels (Moldan et al., 2012). A closely related approach is the Ecosystem service indicator framework that has been applied to assess the status of biodiversity and ecosystems throughout Europe (Maes et al., 2012, 2016). A similar assessment using sustainability or ecosystem service indicator frameworks could be done to assess the status, trends and sustainability of mining in the Arctic region.

However, many challenges remain to be solved in the international assessments, such as considerable differences in the availability and quality of data. Considering ecosystem services, there is a lack of indicators for cultural services, and the number of indicators to assess the demand and valuation of ecosystem services is still low (Maes et al., 2016). Furthermore, the legal dimension is missing in these indicator frameworks. While each country has its own institutional arrangements and traditions, comparative legal research could reveal innovative solutions adopted elsewhere and contribute to the development of the legal governance of Arctic mining.

Development of holistic economic assessment methods is needed to better tackle linkages between resource-based industries and livelihoods and the interplay between industrial development and the provision of public and societal services in the Arctic. The economic models (i.e. input-output models and computable general equilibrium models) applied in the reviewed publications may not have accurately captured impacts on public and social services, such as improved healthcare, education, and infrastructure due to mining operations which are likely to be crucial elements for the socio-economic viability of remote areas. For example, Hajkowicz et al. (2011) found a positive link between the gross value of mining and incomes, housing affordability, communication access, education and employment in regional and remote Australia. In addition, the economic models were not able to capture all the relevant interindustry linkages, often because the methods were based on market transactions omitting externalities that reduce the quality of surrounding environment. A high-quality environment is a key factor for many nature-based livelihoods. Environmental valuation methods can be used to assess the economic importance of the external environmental and social effects of mining (see e.g. Ivanova and Rolfe, 2011; Windle and Rolfe, 2013), but so far this approach seems to be underutilized in the context of Arctic mining.

Topics related to the social sustainability of mining require more attention in the research. SLO is still missing in many countries (Suopajärvi, 2013; Nygaard, 2016), which indicates that the consequences of the practical implementation of SLOs are still largely unidentified. Self-regulation, which is adopted by practically all large mining companies, is important for achieving a SLO and to create trust between the companies and local communities (Nysten-Haarala et al., 2015). However, their assessment is rarely obligatory, or at least, no action based on the results is required of companies (exception: Greenland, Hansen and Mortensen, 2013). Hence there is a need for research that assesses the effectiveness of self-regulation to mitigate detrimental social impacts. Furthermore, IBA or community development agreements in regard to other than indigenous populations were not dealt with in the publications. A trial for making a local benefit agreement in non-indigenous contexts is being done in Sodankylä, in Finland, but due to a lack a best practices approach this is difficult (Municipality of Sodankylä, 2017). Conflict resolution would benefit from new participation methods that can be applied to reveal people's preferences for land uses. Public Participation methods using Geographic Information System (PPGIS) help promote the inclusion of marginalized or under-represented populations in the development (Brown and Kyttä, 2014) and it is expected to apply well to rural Arctic communities. PPGIS has already been used to identify potential land use conflicts in situations where incompatible activities, such as mining and tourism, clash in the same location (Brown et al., 2017).

The mitigation hierarchy is of particular relevance for the Arctic regions where the economy is to large extent based on the exploitation of natural resources, which may cause significant losses of biodiversity. There were no publications on the mitigation hierarchy and its four

steps, namely avoidance, minimization, rehabilitation and ecological compensation for the Arctic region. Successful implementation of a mitigation hierarchy may provide benefits both for nature conservation and economic development (Lapeyre et al., 2015). The mitigation hierarchy and its associated principles (European Commission, 2011) are generally accepted, but there are still only rare regulatory tools that aim to ensure the full use of the mitigation hierarchy which are relevant for mining in the Arctic. Ecological compensation and other measures for implementing the mitigation hierarchy are taken before mining starts, which at least to some extent may mitigate challenging situations, when a mining company goes bankrupt and there are no financial resources available. Ecological compensation has also raised doubts as to whether it can really achieve the goal it is aiming to achieve (Quétier and Lavorel, 2011), and hence further research into its applicability to the Arctic region would be required.

6. Conclusion: lessons to learn considering the sustainability of mining in the Arctic region

Mining is a significant but controversial industry in the Arctic. It supports the local and regional economic development while simultaneously causing long-term negative impacts to the surrounding biotic and abiotic environment. The benefits and costs of mining occur on different temporal and spatial scales and are tied to the scale of the mining operations, the ongoing market situation, the quality of the mine management and planning, and the legal frame under which the mining is done.

The costs of mining in terms of deterioration to the environment are long-term, and global level changes in the climate may cause unforeseen impacts to Arctic mining environments. In order to increase a balanced knowledge base for sustainable mining, environmental research should focus more on the prediction of potential changes, which could be used to mitigate or reclaim the most adverse impacts of mining. Research on the legal dimension should provide information that promotes the adaptiveness of environmental regulation to changes occurring during mining. The economic dimension calls for research on holistic economic assessment methods and on mechanisms and practices that support the diversification of economies in resource-based Arctic regions. The social dimension calls for research into impact and benefit agreements and community development agreements in regard to other than indigenous populations, and to examine the post-mining perspectives of resource-based societies. Multi-disciplinary research on ecological compensation and other measures of the mitigation hierarchy are needed to reduce the detrimental impacts of mining on biodiversity. Monitoring the sustainability of mining is also called for and this could be carried out using standardized indicators that tackle all dimensions of sustainability.

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